Specifications for the Line-of-Sight Laser-Based Signal Transmission of the Recycler Stochastic Cooling Systems

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1. Introduction

The Recycler ring is a storage ring designed to accumulate and cool a particle beam composed of antiprotons. Whereas the eventual method of emittance reduction will be electron cooling, the initial method will be stochastic cooling. It is therefore important to understand how to implement horizontal, vertical, and momentum cooling systems.

It turns out that one of the two major normal arcs is necessary in order to for a pickup electrode derived beam signal to cut a chord and meet the beam at the kicker electrodes. Because of the existence of obstacles on the MI-50 side of the Reycler, the MI-20 side was chosen.

2. Antiproton Considerations

For the horizontal and vertical cooling systems, the phase advance between the pickup and kicker must be an odd multiple of 90°. Since the phase advance per cell in the Recycler is 85.387° horizontally and 79.220° vertically, over approximately 35 half cells of distance the differential phase advance can be quite large. As it turns out, if the number of cells between the horizontal (vertical) pickup and kicker is 18 (17) cells, then the number of betatron oscillations between them is 4.27 (3.74). This corresponds to a horizontal (vertical) net phase advance of 97° (94°), more than close enough to obtain optimal cooling rates.

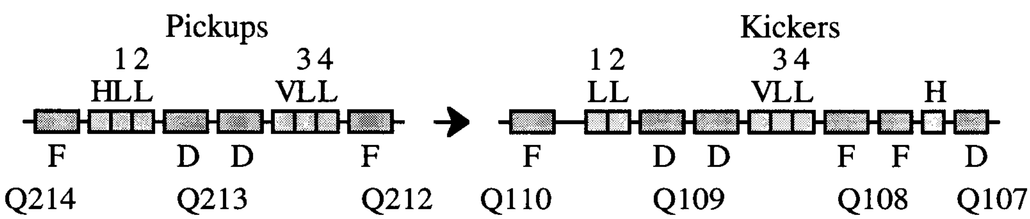


Figure 2.1: Geometry required to implement stochastic cooling in the Recycler ring.

Figure 2.1 shows the tank placement of the horizontal, vertical, and momentum pickup and kicker tanks to achieve the required relative betatron phase advance between the horizontal and vertical systems. There is 163.6 in. between the beam position monitors in the straight sections between pairs of normal arc gradient magnets. The pickup tanks are 54 in. long each. Therefore, three tanks just fit in each half cell.

The kinetic energy of the antiprotons is 8.000 GeV. Table 2.1 summarizes the kinematics of the antiprotons for the stochastic cooling systems. Note that the antiprotons travel about 0.5% below the speed of light, a significant amount given how close the signal transmission and beam propagation delays will be to one another.

Table 2.1: Kinematic considerations for the antiprotons in the Recycler ring.

Parameter	Value
Antiproton Kinetic Energy (GeV)	8.000
Antiproton Mass (GeV)	0.93827231
Antiproton Total Energy (GeV)	8.938
Antiproton Momentum (GeV/c)	8.889
Antiproton Relativistic Energy	9.52631
Antiproton Relativistic Velocity	0.994475
Speed of Light in Vacuum (m/ns)	0.299792458

3. Lattice Considerations

This region of the Recycler lattice is regular, with only the normal arc cell type (except for the horizontal kicker tank in a dispersion suppression cell). On the other hand, there are some injection devices which will limit the flexibility one may otherwise have placing tanks.

The most important limitation is the existence of the MI-22 transfer line and Lambertson. Aiming toward MI-30, the transfer line is terminated at the Lambertson just downstream of the gradient magnets over MIQ214 (between MIQ214 and MIQ215). Therefore, the most downstream position available for placement of a stochastic cooling pickup is the straight section between MIQ213 and MIQ214). The most upstream limit of the normal arc cell section is MIQ108, for a total of 17.5 cells. Since 18 cells are required in the horizontal plane, the horizontal kicker tank must reside in the first dispersion suppression cell. The length of available straight section in a dispersion suppression half cell is 102.1 in., too small for even two tanks.

The one big disadvantage of this geometry is that the horizontal pickup is only 11.6 m away from the injection Lambertson. This means that the horizontal pickup must have the full horizontal aperture of 3.8", which desensitizes the system dramatically. One option is to use a 4 electrode geometry for the horizontal pickup, which has no horizontal aperture restriction and a higher horizontal sensitivity.

Table 3.1: Downstream longitudinal coordinates of the pickup and kicker tanks in the Recycler. These numbers were lifted from the mechanical drawings generated by Terry Anderson for the vacuum system.

Parameter	Pickup	Kicker	Distance
Horizontal Coordinate (ft.)	6601.152	8637.519	2036.367
Longitudinal #1 Coordinate (ft.)	6605.652	8534.120	1928.468
Longitudinal #2 Coordinate (ft.)	6610.152	8538.620	1928.468
Vertical Coordinate (ft.)	6657.872	8586.340	1928.468
Longitudinal #3 Coordinate (ft.)	6662.372	8590.840	1928.468
Longitudinal #4 Coordinate (ft.)	6666.872	8595.340	1928.468

From mechanical drawings of the Recycler ring the beamline distance coordinates of the (proton direction) downstream end of each pickup and kicker tank can be determined. The data is presented in table 3.1 Plugging this information into the data shown in table 2.1, enough information exists to calculate the distance between the pickup and kicker tanks of each of the four stochastic cooling systems. These distances are shown in table 3.2.

Table 3.2: Timing considerations for the stochastic cooling systems for the actual Recycler geometry.

Parameter	Value
Feet per Meter Conversion	3.280839895
Horizontal Distance (m)	620.685
Longitudinal #1 Distance (m)	587.797
Longitudinal #2 Distance (m)	587.797
Vertical Distance (m)	587.797
Longitudinal #3 Distance (m)	587.797
Longitudinal #4 Distance (m)	587.797
Horizontal Distance (ns)	2082
Longitudinal #1 Distance (ns)	1972
Longitudinal #2 Distance (ns)	1972
Vertical Distance (ns)	1972
Longitudinal #3 Distance (ns)	1972
Longitudinal #4 Distance (ns)	1972

4. Signal Transmission Geometry

Because the shortest distance is usually via a straight line, and because of surface obstacles which limit the placement of the trench into which the vacuum pipe transmitting the laser beams is placed, the vacuum pipe and accompanying enclosures and conduits fall on the chord between MIQ213 and MIQ109. The site coordinates for these quadrupoles are known and listed in table 4.1. Note that the typical grade elevation in this section of the ring is approximately 740'.

Table 4.1: Site coordinates for the Main Injector quadrupole centers which determine the signal transmission path for the Recycler stochastic cooling systems.

Parameter	MIQ213	MIQ109
Project Coordinate X (ft.)	98960.55221	99356.30336
Project Coordinate Y (ft.)	95391.83193	97117.96262
Nominal Recycler Elevation (ft.)	720.5	720.5
Longitudinal Distance (ft.)	6636.000	8565.000

Table 4.2: Calculation of the relative angles between the Recycler ring tangent and the chord at the two quadrupoles.

Parameter	MIQ213	MIQ109
Chord Angle (deg.)	257.1	257.1
Recycler Tangent Angle (deg.)	297.7	36.5
Relative Angle (deg.)	40.6	40.6
Cosine of the Relative Angle	0.759	0.759
Sine of the Relative Angle	0.651	0.651

The angle between this chord and the ring itself is calculated in table 4.2. The definition of angle is

$$\theta = \arctan\left(\frac{\Delta Y}{\Delta X}\right) \quad . \qquad (4.1)$$

The minimum distance between the closest tunnel wall and the location of the laser launch cave is 26' in order for the enclosure to not be a controlled radiation area. Therefore, the minimum distance between the tunnel and cave along the chord is 40' = 12 m. This also means that the width of the berm above the tunnel is elongated by approximately 40% to about 70'. In figure 4.1 is a sketch of the tunnel/chord configuration on either side of the chord assuming that all signal transmission is on the chord until the cables are in the Main Injector tunnel..

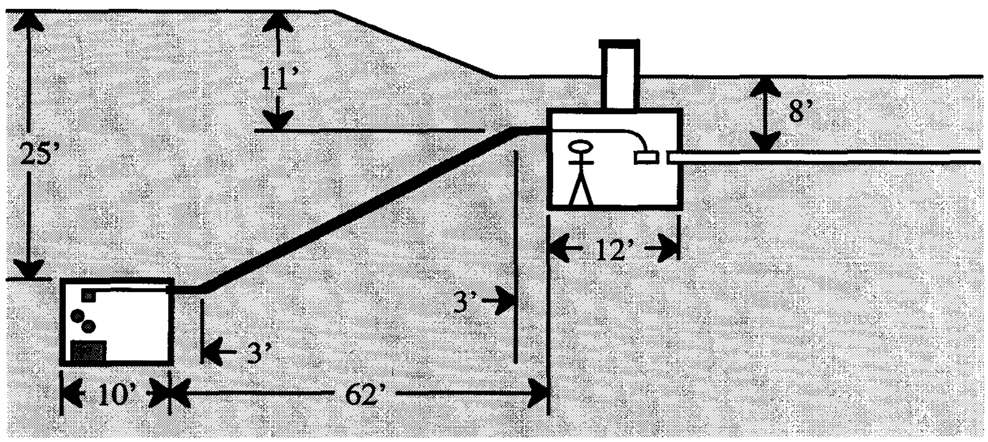


Figure 4.1: Sketch of the geometry used in signal delay calculations presented in this paper. This is the elevation view along the length of the chord between MIQ213 and MIQ109.

This assumption that all signal parthways between pickup and kicer tanks are either vertical, along the chord, or along the beamline is not realistic due to transmission delay shortages. Because we need to decrease the delay in the signal transmission, the first method for reducing delays without compromising performance is to invoke more civil construction. The change is to leave the path of the chord between the laser enclosure and tunnel and have direct conduits to each half cell, thereby eliminating the majority of the transmission line delay along the beamline. Figures 4.2 contains a sketch of the geometry.

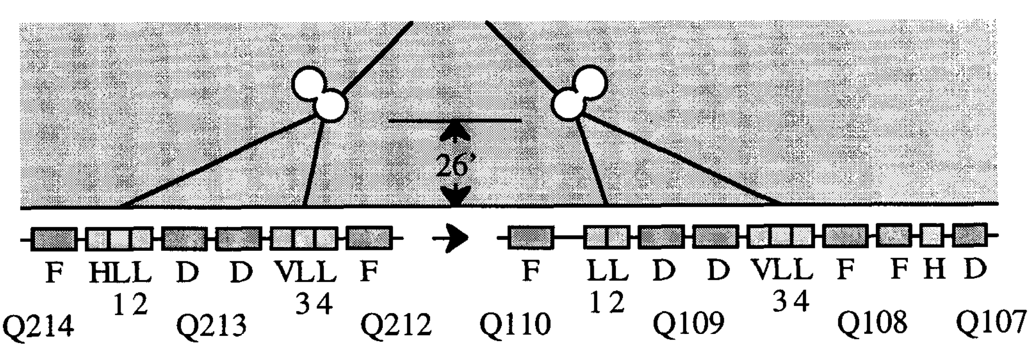


Figure 4.2: Plan view of the proposed conduit configuration between the laser telescope caves and the Recycler tunnel.

The shape of the laser cave is due to confined space regulations and the desire to avoid that designation for these enclosures. Basically, the problem is that one needs a stairwell in order to avoid confined space classification. By using the "peanut" geometry used in the MI-60 cooling pond pump enclosure, one side (the side on the chord) can be used for electron cooling hardware while the other identical side contains a spiral staircase along the wall of the 12' diameter cylinder. These metalic cylindrical enclosures which are slightly overlapping and joined are 9' tall and come with personell and equipment hatches which extend far enough above the ground to prevent flood damage to the electronics.

The minimum requirement for the telescope pipe which is buried 8' below grade is that it contains the 6 2" diameter laser beams for the 6 stochastic cooling system. Figure 4.3 contains a sketch of the minimual configuation assuming no misalignments and an effective 4" diameter for the beam for lense systems and halo. If one assumes that the pipe, which is 1637' long, heaves and shifts by ±6", then the pipe diameter must be 2 ft.

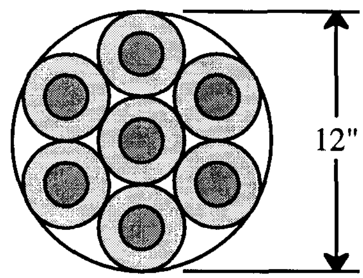


Figure 4.3: Minimal laser pipe diameter to house the 6 laser beams which are 2" in diameter with a 4" diameter halo. A seventh laser is allowed without an increase in the diameter of the pipe.

At this point the delay due to the laser telescope itself needs to be calculated. The results are tabulated in table 4.3.

Table 4.3: Length of the signal pathways along the chord between MIQ213 and MIQ109.

Parameter	Value
Total Length of the Chord (ft.)	1771
Length of the Laser Telescope (ft.)	1657
Delay in Laser Telescope (ns)	1685

Table 4.4: Calculation of the signal delay in coaxial cable.

Parameter	Value
Speed of Light in Vacuum (m/ns)	0.299792458
Feet per Meter Conversion	3.280839895
Signal Speed in Fiber Optics (c)	88%
Nanoseconds per Foot in Fiber	1.16

The optimum cooling system would have the fiber optic laser transmitter and laser reciever at the pickup and kicker tanks. This is also the most conservative assumption for the calculations in this paper, since the propagation velocity of a signal in optical fiber is 67% of the speed of light, whereas the propagation velocity in good coaxial cable is 88%

of the speed of light. Unfortunately, it has already been determined that there is no possible geometry in which works when optical fiber carris the signal between the tunnel and the laser telescope. Therefore, coaxial cable is used in the calculations in table 4.4.

There are other delays in a stochastic cooling system. The laser transmitter and reciever each have a delay associated with them. Similarly, amplifiers, attenuators, switches, and delay trombones all have delays associated with them. Finally, it takes time for the signal generated on the pickup electrode (and the kicker signal delivered to the kicker electrodes) to get to (come from) the electrical port on the vacuum tank. Standard numbers quoted by Ralph Pasquinelli for each of these sources of delay are listed in table 4.5.

Table 4.5: Miscellaneous delays in a standard stochastic cooling system.

Stochastic Cooling Component	Delay (ns)
Pickup Tank from Arrays to Port	5
Pickup Amplifiers and Trombones	5
Laser Transmittter	15
Miscellaneous Connecting Cables	15
Laser Link Reciever	15
Kicker Electronics	5
TWT	15
Kicker Tank from Port to Arrays	5
Total	80

Because the signal delay in all other geometries is too long, it is necessary to have inclined conduits between the tunnel and the laser telescope. Table 4.6 contains the lengths of the various conduits, and the distance along the tunnel that the signals must travel to reach the FAR end of the relevant pickup and kicker tanks.

Table 4.6: Signal transmission distances in the coaxial cables of each of the 6 stochastic cooling systems for the Recycler ring.

Parameter	H	L1	L2	V	L3	L4
Transmission Across Tunnel (ft.)	20	20	20	20	20	20
Transmission Across Cave (ft.)	18	18	18	18	18	18
Length of Pickup Conduits (ft.)	70.2	70.2	70.2	33.0	33.0	33.0
Length of Kicker Conduits (ft.)	70.2	33.7	33.7	70.2	70.2	70.2
Length along Pickup Beamline (ft.)	4.5	0	4.5	4.5	0	4.5
Length along Kicker Beamline (ft.)	46.7	2.3	2.3	4.5	0	4.5
Total (ft.)	229.6	144.2	148.7	150.2	141.2	150.2

Adding together all of the delays, the total signal delay for each stochasti cooling system is listed in table 4.7. Note that these numbers represent fairly conservative numbers and could be shortened by a number of techniques if required. The minimum margin is 32 ns, which is enough to make me confortable with the level of estimation.

Table 4.7: Signal transmission delays in each of the 6 stochastic cooling systems for the Recycler ring. All delays are rounded up to the next integer number of nanoseconds.

Parameter	H	L1	L2	V	L3	L4
Miscellaneous Delays (ns)	80	80	80	80	80	80
Laser Telescope Delay (ns)	1685	1685	1685	1685	1685	1685
Coaxial Cable Delay (ns)	267	168	173	175	164	175
SubTotal	2032	1933	1938	1940	1929	1940
Beam Path Delay (ns) [from T.3.2]	2082	1972	1972	1972	1972	1972
Amount Signal Beats Beam (ns)	50	39	34	32	43	32

5. Civil Construction Issues

5.1. Buried Pipe

The laser telescope pipe must have a 2 ft. inside diameter, with a wall thickness which is arbitrary as far as the function of the telescope is concerned. The pipe must be optically straight between the pickup and kicker caves. There must be a blower-type vacuum roughing pump in either cave pumping on the pipe. The pipe must be optically straight with an initial tolerance of ±3 in. in order to allow an additional ±3 in. of subsequent heave.

The conduits between the tunnel and caves may have approximately 3' of horizontal run on either end, but the vast majority of the conduit must be a straight slant in order to minimize signal delays.

5.2. Buried Caves

The interface between the cave and the tube can be welded. The caves must not be classified as a confined space. The vacuum blowers in the cave must be mounted in such as was as to minimize vibrations to the cave structure. The services required are listed below in table 5.1.

Table 5.1: Utility services required in caves.

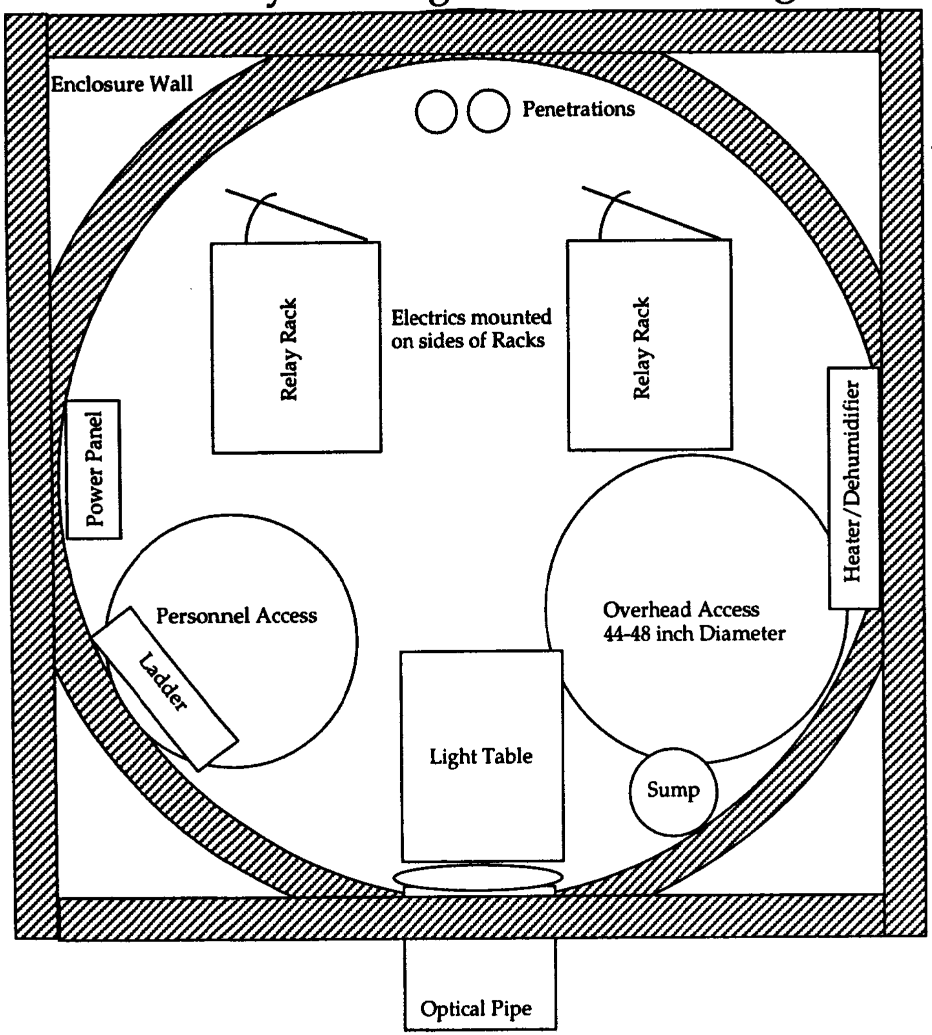
	Pickup Cave	Kicker Cave
Utility Power (120 V)	2x 20 Amp circuits	2x 20 Amp circuits
Heat from Electronics	5 kW	6 kW
Utility Power (208 3-phase)	18 kW	0

5.3. Cave Geometry

See the attachment.

Recycler Ring Stochastic Cooling Enclosure Requirements

Ralph J. Pasquinelli
10/29/97



Power Requirements/ Heat Dissipation

Kicker Side:
Maximum of 6 TWTs or Solid state amps
208 /3 phase VAC 2.5 KWatts each.
Utility power, two 20 amp 120 VAC
Electrical heat disipation due to electronics in enclosure is 800 watts per TWT max plus 1 KWatt from utility power for a total of approximately 6 KWatts

Pickup Side:
Utility power, two 20 amp 120 VAC
Electrical heat dissipation due to electronics in enclosure is 1 KWatt from utility power.

10x10 foot or 10 foot dia.
circular enclosure